The Skaw Spit

a question of settlements

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The Skaw Spit - a question of settlements

[87]

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SYNOPSIS: This paper presents results of analyses of oedometer tests carried out with samples from a boring at the outermost point of the Skaw Spit. In an attempt to improve the understanding of the interaction between the consolidation and the creep deformations, the results of the tests have been analysed by a model to separate creep and consolidation set up by Moust Jacobsen. The results of the oedometer tests have previously been analysed by means of different methods to determine the preconsolidation pressure.

The analyses have been carried out in connection with investigations in progress at and around the Skaw Spit to explain the geological structure and the land movements in the area.

1. INTRODUCTION

The top of Denmark is a spit, the Skaw Spit (Skagen Odde), formed since the Weichselian Ice Age by marine sedimentations. The outermost part of the spit, the Grenen Point, emerged during the latest few centuries.

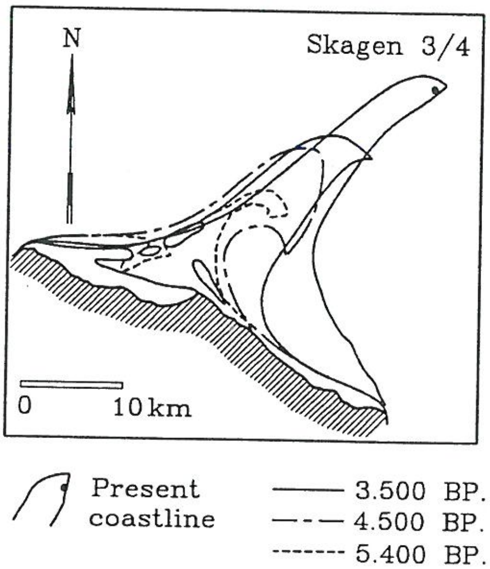

Fig. 1. Development of the Skaw Spit. (Hauerbach, 1992).

1.1 *Levellings*

Levellings on the Skaw Spit carried out in 1942, 1953, 1983 and 1991 have indicated, that the youngest part of the spit does not follow the general uplift of the northern part of Denmark (Hauerbach, 1992).

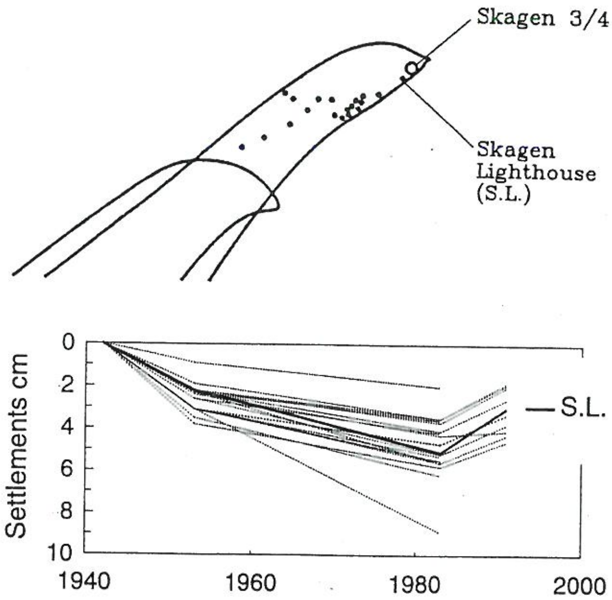

Fig. 2. Relative movements 1942-91 of the outermost part of the Skaw Spit (Hauerbach, 1992).

1.2 *Geological investigations*

The area has been the subject of several geological investigations through the years.

A study of the foraminiferal faunas in samples from an older boring in the area (Knudsen, 1985) has indicated an unusual thickness of very young sediments at the Skaw Spit.

Seismic investigations have been carried out around the Skaw Spit in an integrated geological research project, the GeoKat project, run at the Department of Earth Sciences, University of Aarhus. The results of these investigations confirmed the thickness of very young sediments (Lykke-Andersen & Knudsen, 1992, Lykke-Andersen et. al 1993a & b). A boring to 220 meters below the surface, the Skagen 3 boring, was carried out in 1992 in connection with the GeoKat project.

2. THE BORINGS SKAGEN 3 / 4

2.1 *Sampling*

The Skagen 3 boring was carried out as a rotary boring with continuous coring from the depth of 30 m. In the Holocene silt and clay layers, undisturbed 70 mm diameter samples were extracted and vane tests carried out at 3 to 6 meters intervals. In 1993 a new boring, Skagen 4, was carried out as a cable percussion boring with continuous Split Spoon sampling through the upper 30 m "Odde"sand.

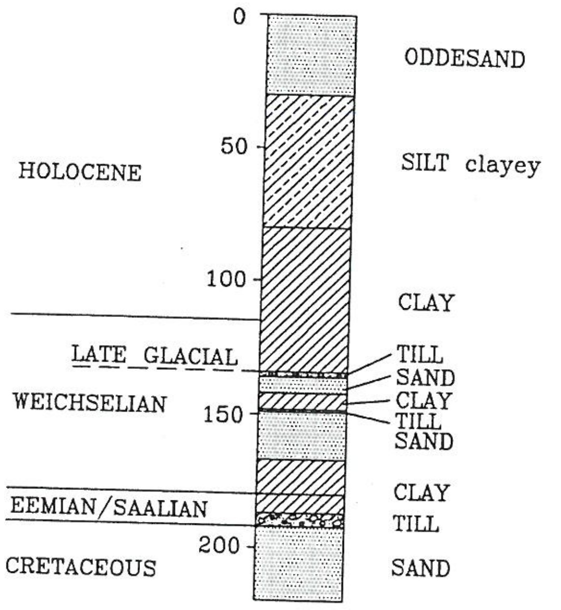

Fig. 3. Skagen 3 boring (Knudsen, 1994).

The material from the borings is being studied as a research project by the GeoKat group at the University of Aarhus in cooperation with "The Skagen Spit project -nature and culture", The Geological Survey of Denmark, The University of Cambridge and Aalborg University.

2.2 *Vane tests*

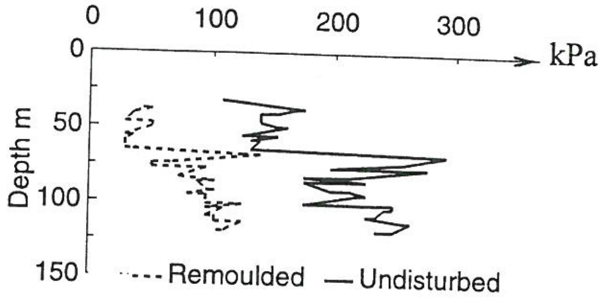

Fig. 4. Undrained shear strength measured by vane.

2.3 *Age of the sediments*

The Eemian clay has an age of about 120.000 years, the Weichselian clay in the depth of 143 m is about 20.000 years old and the Late Glacial sediments about 15.000 years old.

Samples of foraminifera and shells from the marine Holocene sediments have been radiocarbon dated by Accelerator Mass Spectrometry (AMS) (Conradsen & Nielsen, in press):

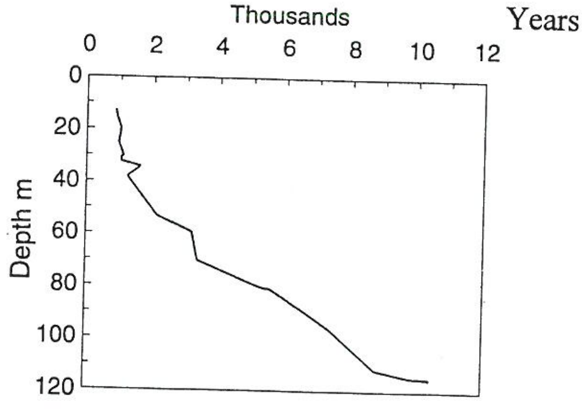

Fig. 5. Results of ^{14}C datings from Holocene sediments (Conradsen & Nielsen, in press).

The sedimentation rate has been very high, 70 mm/year, from 30 to 12 m below surface. In the upper 12 m there are no datings because of lack of shells and foraminifera.

2.4 *Geotechnical laboratory tests*
Classification tests and oedometer tests have been carried out with the majority of the undisturbed samples from the Holocene sediments and also with some samples from the cores of Late Glacial and older sediments.

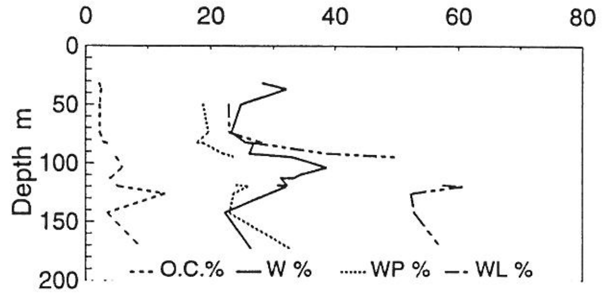

Fig. 6. Water content, Atterberg limits and loss of ignition, O.C., for the tested samples.

The oedometer tests have been carried out with 60 mm samples in The Danish Consolidation Apparatus (Moust Jacobsen, 1967).

Different methods have previously been used to analyse the test results in order to estimate the preconsolidation pressures of the sediments (Thorsen, 1994, in press).

The results of these analyses indicated, that the consolidation process caused by the load of the "Odde"sand is completed. However, the values of OCR in the Holocene clay sediments are found the be very close to 1.

There are no undisturbed samples from 94 m to 103 meters depth, but the results of the vane tests do not indicate any significant changes in the state of consolidation of the sediments.

3. MOUST JACOBSEN'S MODEL

Moust Jacobsen has set up a model to separate creep and consolidation deformations during the consolidation process (Moust Jacobsen, 1992). He assumed the consolidation and creep to be simultaneous and has described the creep as

$$\varepsilon_{cr} = Q_s \log(1 + \tfrac{t_r}{t_b}) \qquad (1)$$

Qs = rate of creep for $\sigma' \geq \sigma'_{pc}$
t_r is the real time from start of creep
t_b is a reference time

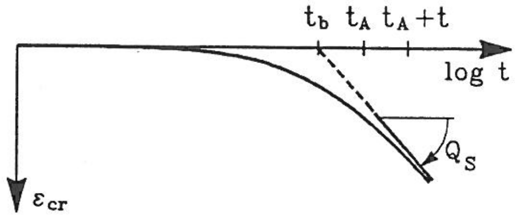

Fig. 7. The creep curve.

If a sample is under constant pressure from a time t_A to a time $t_A + t$, the additional creep is

$$\Delta\varepsilon_{cr} = Q_s \log(1 + \tfrac{t}{t_A + t_b}) \sim Q_s \log(1 + \tfrac{t}{t_A})$$
if t_b is small compared to t_A.
t_A represents the total creep age, and is often assumed to be the geological age of a soil in a normally consolidated state.

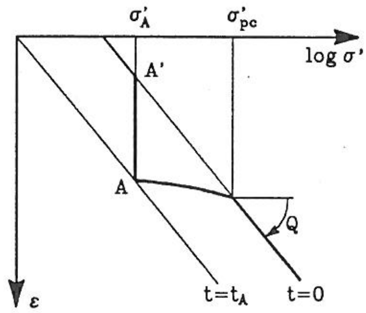

Fig. 8. Behavior of slightly preconsolidated clay (Moust Jacobsen, 1992).

Moust Jacobsen assumed that the same value of the strain, ε, could be obtained in two ways:
1) a strain on a primary curve from σ'_A to σ'_{pc}
$$\Delta\varepsilon_c = Q \log(\tfrac{\sigma'_{pc}}{\sigma'_A})$$
2) a sum of a strain resulting from creep under constant stress to the time t_A
$$\varepsilon_{cr} = Q_s \log(1 + \tfrac{t_A}{t_b})$$
and a strain by reloading from σ'_A to σ'_{pc}
$$\Delta\varepsilon_r = \frac{\sigma'_{pc} - \sigma'_A}{K}$$

This leads to the following formula:

$$\frac{\sigma'_{pc}}{\sigma'_A} = (1 + \tfrac{t_A}{t_b})^{\alpha} \exp(\frac{2.3(\sigma'_{pc} - \sigma'_A)}{QK}) \qquad (2)$$

$\alpha = \frac{Q_s}{Q}$, and K is the average modulus for reloading.

The creep rate in time-settlement curves has proved to be nearly constant after exceeding the preconsolidation pressure. Using this value for Q_s, a creep curve can be determined and subtracted from the time settlement curve.

By separating creep and consolidation, the values of the strain at the end of the consolidation and the time of consolidation as well as the creep age are obtained for each load step in the oedometer tests.

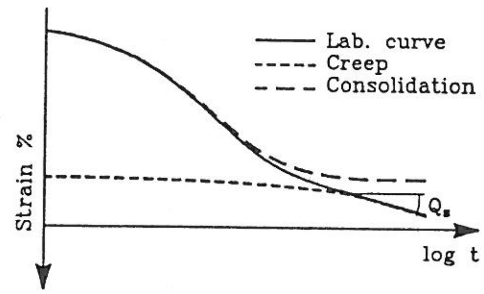

Fig. 9. Separation of creep and consolidation for a soil in a normally consolidated state.

4. RESULTS AND ESTIMATIONS

4.1 *Results of the analyses*

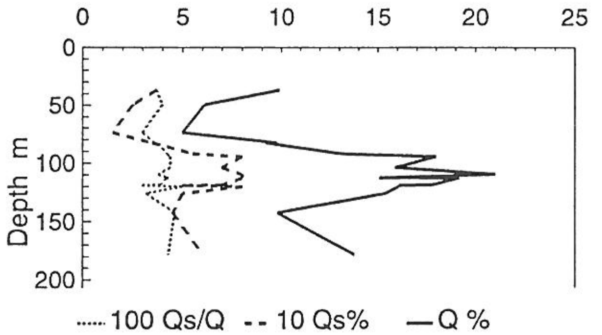

Fig 10. Results of the determinations of Q, Q_s, and α using Moust Jacobsen's model.

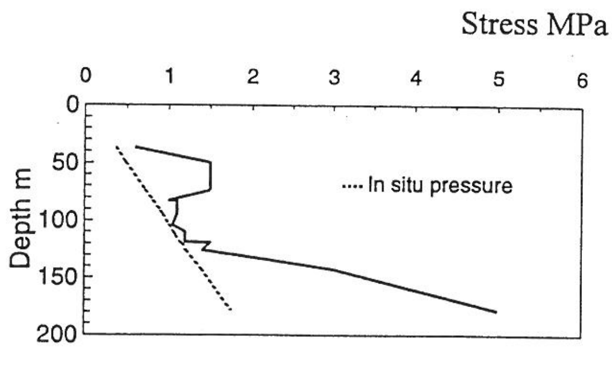

Fig. 11. Determination of σ'_{pc} from the consolidation curve by Moust Jacobsen's model.

As long as the sample is in a reloading state the creep age is greater than the time of consolidation. The creep age is however reduced by each new load step.

At the very moment where the soil is subjected to stresses beyond the preconsolidation pressure, the creep age is in principle reduced to zero.

At the very load step where the stress exceeds σ'_{pc} the creep age is less than or equal to the time of consolidation. If the stress at each new load step exceeds the new value of σ'_{pc}, the creep ages will be nearly constant.

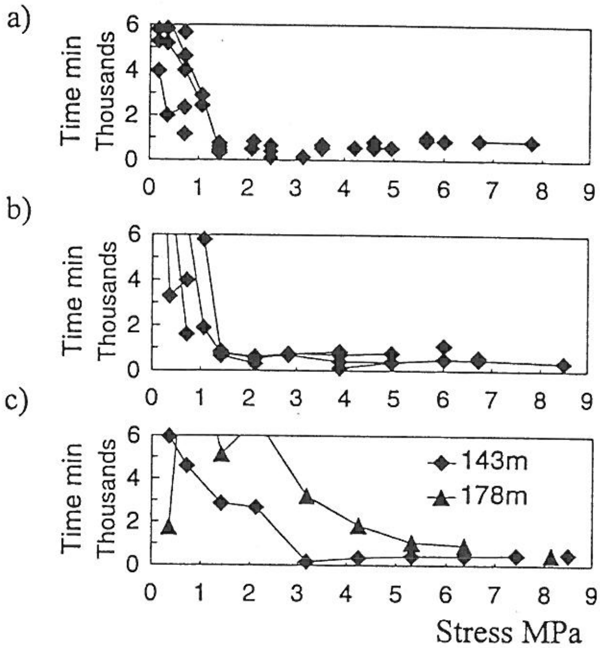

Fig. 12. Determination of creep age

a) *Holocene clay,*
$\sigma'_{in-situ} \sim 0.9\text{-}1.1$ MPa, $t_c \sim 500$ min.

b) *Late Glacial clay,*
$\sigma'_{in-situ} \sim 1.1\text{-}1.3$ MPa, $t_c \sim 500$ min

c) *Clay from 143 m and 178 m*
$\sigma'_{in-situ} \sim 1.4$ and 1.75 MPa, $t_c \sim 500$ min

As shown in Fig. 12 the creep ages for the Holocene and the Late Glacial clays are found to be nearly constant from the step, where the stress exceeds the in situ stress.

For the sample from 143 meters depth and the sample from 178 meters depth the creep age determinations indicate a preconsolidation pressure of more than 2000 kPa and 5000 kPa respectively, corresponding to OCR~1.4 and OCR~2.8.

4.2 *Estimations*

Besides the parameters for the soil, a good modelling of the consolidation and creep processes requires information about the drainage path and the loading scheme.

The determination of creep rate and the influence of creep on the preconsolidation pressure require a determination of the creep age, which is the time passed since the last time a loading has reduced the creep age to zero.

4.2.1 Holocene and Late Glacial clays

The values of OCR ≥ 1 as determined from the oedometer tests indicate that the consolidation is completed after the latest loading.

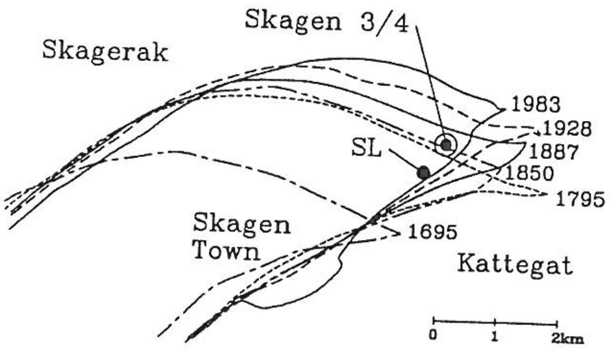

Fig. 13. The changing position of the outermost part of the Skaw Spit (Hauerbach, 1992).

Fig. 13 shows, that the Skagen 3 boring is placed close to the existing coastline 200 years ago. Since the area just outside the coast of a spit has a very low water depth, most of the upper 12 m of the "Odde"sand must have been sedimented more than 200 years ago. The town of Skagen has been land area for more than 300 years. On the basis of this and OCR ≥ 1 we may assume the time of consolidation to be more than 200 years.

If a consolidation process is completed, the minimum value of the creep age t_A, is $t_A = t_b$, and since the consolidation and creep are assumed to be simultaneous, the minimum creep age at the end of the consolidation process is the time of consolidation. The creep during the consolidation process is then:

$$\varepsilon_{cr} = Q_s \log(1 + \frac{t_c}{t_c})$$

and from formula (2) the creep during the consolidation process will give an OCR~1.03.

Assuming the creep age of the Holocene and Late Glacial sediments to be only 2-300 years, the present creep rate $\frac{d\varepsilon}{d \log t}$ can be calculated to less than 0.5 mm/ year, compared with the observed settlements of 1-2 mm/ year.

4.2.2 Weichselian and Eemian clays

For the samples of clay from 143 and 178 meter's depth, a calculation from formula (2) on the basis of the geological age and the parameters determined from the consolidation tests gives OCR~1.6 and OCR~2.7 respectively, the same magnitude as found by the conventional determinations of σ'_{pc}.

This may indicate, that the preconsolidation could have been obtained by creep only, if the sedimentation of the "Odde"sand has had no real influence on the creep age in these deposits. More investigations have to be carried out to verify this.

5. CONCLUDING REMARKS

The oedometer tests have been analysed by the model set up by Moust Jacobsen. Further investigations are in progress and promise well for an improved understanding of the interaction of creep and consolidation.

The results of the investigations so far indicate, that the consolidation process in the Holocene sediments caused by the sedimentation of the "Odde"sand is completed, and the estimated creep settlements are below the observed settlements in the area.

The results also indicate, that the OCR values of the Holocene clay are very close to 1, which means, that a sudden increase in stress may result in an exceeding of σ'_{pc}.

The sediments below the town of Skagen may be very similar to the sediments at the Grenen point as indicated by Johnny Fredericia (Fredericia, 1988) and by the seismic investigation along the coast SE of the town (Lykke-Andersen & Knudsen, 1992).

In that case the fillings of some meters of sand in the new part of the harbour should have introduced some settlements locally.

Investigations in the Skaw Spit area are still in progress and a boring in the town of Skagen is to be carried out within a very short time.

Even if the oedometer tests indicate a completion of the consolidation process, excess pressure in the pores may exist in some parts of the sediments. In the Skagen 3 boring a gas production was observed in the Holocene clay sediments, and the transformation of organic material to gas may result in an increase in volume followed by an increase in pressure until this is high enough for the gas to escape. The seismic investigations around the Grenen Point have also indicated leaking of gas.

In a seismic profile run along the coastline SE of Skagen a fault has been observed as shown at Fig. 14. The direction SE-NW is indicated by other profiles in the area (Lykke-Andersen & Knudsen, 1992).

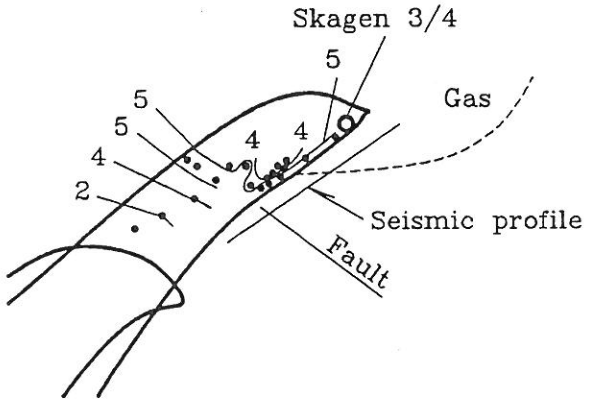

Fig. 14. Settlements (cm) 1942-83, and results from seismic investigations (Lykke-Andersen & Knudsen, 1992, and Hauerbach, 1992).

As seen in Fig. 2 the levellings in 1991 showed an upheaval compared to the levelling in 1983. If this is the case, the movements in the area may be influenced by other factors than settlements in the Holocene sediments.

An investigation of the relative movements in the area by Kai Borre, Aalborg University, using the Globale Position System (GPS) has been started in 1993. New levellings by the National Survey and Cadastre are also in progress in the area and the results will be available at the end of the year.

The results of the levellings and the GPS measurements together with the results of the new boring in the town of Skagen are expected to improve the understanding of the movements in the area.

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